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IGNITION CHARACTERISTICS OF GAS TURBINE LUBRICATION OILS

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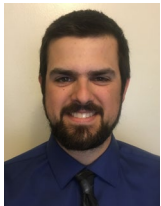
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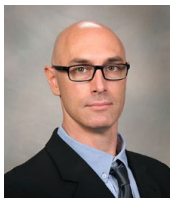
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ABSTRACT

Ignition of lubricating oil is a highly undesirable event that is a major safety hazard that could also be incredibly costly. The possibility for lubricant ignition is present in numerous mechanical systems and applications. To better understand this possibility, an extensive review of the literature reveals the applications affected by this hazard and methods that have been applied to understand the underlying causes. While some work has been completed in this area, the fundamental chemical kinetics of lubricant ignition remains widely unknown. A shock-tube experiment was hence developed and implemented to collect fundamental ignition delay time (τ_{ign}) measurements of lubricants at high temperatures. The shock tube is used to generate high-temperature air, and an automotive injector is used to spray lubricant into the high-temperature air. Combustion of the lubricant is then observed using pressure and chemiluminescence diagnostics. Several key features are observed in the resulting τ_{ign} curve from the experiments, and these observations are briefly described and discussed. A second experiment, designed to characterize the propensity of an oil to ignite when touching a hot surface was also developed, called the hot-surface ignition experiment. Initial results from this experiment demonstrate the ability to determine a minimum ignition temperature for an off-the-shelf gas turbine lubrication oil.

INTRODUCTION

Power generation in the United States is produced largely using natural gas by about 40% on average across the U.S. (Kwon, 2017). Over 80% of energy from natural gas is produced using gas turbines. The systems in general operate with greater than 600°C exhaust temperatures that result in around 120°C operating temperatures for turbine subsystem components (i.e. bearings, etc.). Gas turbines like the high efficiency (63%) 7HA class of gas turbines from General Electric require higher temperatures and pressures, as well as reduced friction, to achieve this efficiency and still meet regulatory requirements (Vandervort et al., 2019). Lubricants are at the center of this high efficiency as they not only provide the required reduction in friction for the components, but also remove heat from these components experiencing these elevated temperatures (Levy et al. 2004). The base oil consists of a collection of large hydrocarbons to which additional ingredients are added: anti-oxidants, detergents, corrosion inhibitors, demulsifiers, and anti-foaming agents to name a few. These additives usually make up 0.5-5% of the lubricant. Oils are chosen as the base for lubricants for a number of reasons including their low reactivity. Unlike their smaller counterparts, long-chain hydrocarbons have the advantage of long-term stability allowing for extended periods of heat cycling before breaking down and changing properties. However, as with any molecule, with enough heat and time the long hydrocarbon chains will break down.

Changing these lubricants is incredibly costly, requiring for example thousands of gallons in the 7HA systems and significant downtime, forcing the lubricants to endure these elevated temperatures for extended periods. Extended exposure of a lubricating oil to heat cycling can lead to hazardous events within and surrounding lubrication chambers (bearings, etc.). Not only is the oil itself degrading, but many of the additives, such as anti-oxidants, are sacrificial in nature and are consumed as part of their protective duty. Additionally, during extended use the lubricant tends to mix extensively with oxidizer (air), quickly consuming anti-oxidants. In applications with particularly high surface temperatures (> 200°C), the lubricant will break down and solidify on the surface to form coke (Brandauer, 1996). All of these non-ideal effects can lead to increased reactivity of the base oil and can lead to auto-ignition resulting in a fire. Explosions caused by heavy oils in *in-situ* combustion (ISC) and air-injection-assisted steam recycling (AASR) further highlight the potential hazard lubricants pose (Huang et al., 2021).

This hazard is not limited to gas turbines, and it also poses a threat to wind power. The high torque required to collect wind energy is transferred through a gear box that can reach elevated temperatures and cause this potential hazard (Sun et al., 2019). A conservative estimate of the number of wind turbine fires suggest a fire will occur once for every 2000 wind turbines each year (Krcmar, 2020). This level of incidence translates to each farm experiencing a fire once per year costing upwards of \$4.5 million in damage and lost revenue due to project shut downs.

Aside from being a fire hazard, lubricants also pose a threat to internal combustion engines (ICEs). Lubricants coat the walls of the combustion chamber in ICEs where droplets of lubricant frequently form (Zhen et al., 2012). These droplets cause hot spots that can lead to premature auto-ignition or low-speed pre-ignition (LSPI). LSPI can then lead to detonation formation causing engine knock and eventually damaging the engine components not designed for such pressures.

As many ingredients are required to make a desirable off-the-shelf lubricant, these mixtures quickly become complicated. Naturally, these formulae are highly proprietary to lubricant manufacturers. While the base oil makes up the vast majority of the mixture (>90%), additives can still have a significant effect on the resulting mixture's reactivity. Therefore, comparing the reactivity of unused lubricants is especially important, particularly for off-the-shelf lubricants where the composition is unknown. Each of these additives, while altering lubricant properties in desirable ways, can be adversely affecting reactivity which has been little explored for both the base oil and the additives themselves. Ergo, significant efforts are required to define relative reactivity between lubricants to provide valuable safety information toward choosing different lubricants for a particular application.

While many methods exist for defining reactivity and flammability, few can be applied to the long-chained hydrocarbons that compose lubricants. Even so, ignition delay time (τ_{ign}) is a very fundamental definition of reactivity. Essentially, τ_{ign} represents how long a compound will take to ignite at a certain pressure and temperature. Particularly if a compound can be brought to these conditions fairly instantaneously and homogeneously, τ_{ign} gives a fundamental look at the chemical reactivity of a compound. Comparing the τ_{ign} between compounds easily shows which compound is more reactive over a range of conditions. To this end, a new experiment was developed to collect τ_{ign} data for off-the-shelf lubricants, allowing for comparison of relative reactivities of lubricating oils. A second experimental device to study the ignition of lubricants on hot surfaces was also developed over the past two years by the authors.

Provided below is a literature review covering various aspects of lubricant oil ignition, including fundamental ignition studies, application-based studies, lubricant ignition in internal combustion engines, lubricant oil composition, shock-tube studies, and hot-surface ignition studies. Following this review of the available literature, the two experimental techniques developed at Texas A&M University (TAMU) are briefly outlined. Finally, some recent results from the shock-tube ignition and hot-surface ignition experiments for common gas turbine lubrication oils are presented.

LITERATURE REVIEW

An extensive literature review was conducted and is detailed here to better understand the problem itself and what has been done thus far to understand it. A summary of the results of this literature study is provided in the following sections.

Fundamental Ignition Studies

The first report on ignition temperature and flammability of engine oils and hydraulic fluids was conducted by Zabetakis et al. (1962). Note, Zabetakis' investigations began with aircraft hydraulic fluid flammability in 1956 (Miller et al. 1956). This initial work on lubricants utilized a high-pressure furnace to collect τ_{ign} data. Ignition delay times were recorded between 1 and 300 atm at temperatures between 200 and 230°C for base mineral oils with τ_{ign} as long as 2 minutes. The focus of the work was to establish minimum autoignition temperatures for these oils at various pressures. Zabetakis et al. (1962) suggested high-pressure τ_{ign} is largely unaffected by small changes in additive composition, but small quantities of additives can have a large effect at near-atmospheric pressure.

Later, Kuchta and Cato (1968) presented a review on the ignition and flammability properties of lubricants. Here, ignition and flammability data are presented for over 90 lubricants and hydraulic fluids at pressures of 0.125-1000 atm. Ignition delay times presented therein are considerably longer than 1 second, with a few examples near 0.3 seconds. Emphasis was placed, however, on the auto-ignition temperatures (AIT) of these lubricants. Generally, the AIT of lubricants decreases with increasing pressure and oxygen concentration. Interestingly, it was noted that there is generally a critical value above which pressure and oxygen concentration have no effect. Overall, Kuchta and Cato (1968) explain there is little information available for predicting and preventing lubricant autoignition, and additional work is required.

Application-Based Studies

While investigations into lubricant ignition are limited, a handful of studies have been conducted for internal combustion (IC) engines, air conditioners, and air- and land-based turbines. Loomis (1976) and Rosenlieb (1973) used a bearing test rig to simulate an aircraft engine sump, wherein an ignitor was used to test lubricant vapor flammability. These reports investigated lubricant sump fires using three different lubricants in a test rig which produced a bearing outer-ring temperature between 550 and 600°F (288 and 316°C), inlet oil temperature from 380 to 400°F (194 to 205°C), and hot air temperature between 800 and 1100°F (427 and 594°C). An ignition source was utilized as spontaneous ignition was not observed in the test rig. In addition, these investigations found fire propagation was retarded when a fire suppressant was mixed into the lubricant. This result was suggested to be mainly the effect of cooling and not chemical in nature. It was also found that a fire-baffle (Monel sheet) was also helpful in mitigating fire propagation and preventing thermal seizure of the bearing due to hot (1200°F or 650°C) gas flow. A main outcome was a moderate effect of lubricant type in varying the ignition temperature. Other identified parameters influencing fires in bearing chambers were chamber design; hot air flow rate and temperature; operating speed; oil flow and temperature; and bearing temperature.

Willenborg et al. (2002) more recently discussed details on oil fires in jet engines and their causes and experimentally studied oil fires in bearing and secondary systems. Specialized facilities were developed to reproduce bearing system conditions. A link between increased occurrence of oil fires and pressure ratio and turbine inlet temperature was also shown due to the increased heat transfer to the oil, indicating this as a recurring and increasing problem in the industry.

In a study from Siregar and Nugroho (2014), large incidences of fires in gas turbines used in the oil and gas industry due to the lubricating oil was mentioned as a motivation for the study. It is stated therein that over half of engine room fires on ships were linked to lubricating oil leakage leading to losses upwards of 4 million USD/year. Auto-ignition was directly observed between 650 and 1020°F (344 and 549°C) in their study. Ignition is described therein as a three-stage process: initial vaporization, fuel vapor and oxidizer mixing, followed by ignition.

Peyton-Bruhl et al. (2019) developed a CFD-based method for predicting oil auto-ignition in gas turbine bearings. This model still requires experimental validation, but describes a potentially flammable oil-air mist within the bearing chamber. This mixture is created by the small mass flow out of the labyrinth seals due to the high-pressure differential. This highly flammable mixture has the possibility to hold a stable flame if the turbulent flame speed is smaller than that of the flow velocity.

An investigation on a series of fires in offshore gas turbines by the Health and Safety Executive (HSE) described the possibility for leaking lubricating oil to ignite well below their auto-ignition temperature (AIT) (Snee et al., 2016). Therein, a Spontaneous Combustion Calorimeter was developed to study spontaneous ignition in lubricants above 660°F (349°C). The effect of lubricant age (in-service) was also investigated, showing no strong influence on ignition temperature. The authors indicate that in laboratory-scale equipment, ignition can occur at temperatures well below the lubricant's minimum ignition temperature. They also state that the findings are limited and need to be repeated and expanded to a wider temperature range under conditions closer to those seen in a gas turbine.

As mentioned earlier, explosions in *in-situ* combustion (ISC) and air injection assisted steam recycling (AASR) caused by lubricating oils have been discussed by Huang et al. (2021). Therein, an explosion testing facility was used to ignite heavy oils within a 645-ml, high-pressure cylinder. AIT are presented for pressures up to 15 MPa using piloted ignition and gradual heating. Most notably, Huang et al. (2021) show that heavy diesel can be more flammable than lubricating oils. It was noted that heavy oil is particularly vulnerable to spontaneous combustion, and lower autoignition points were observed for heavier oils. This lower ignition point is attributed to the higher resin and asphaltene content of heavy oil allowing the higher viscosity to allow coke to be readily available to oxidation.

Further potential for lubricant ignition has been shown for an air conditioner system due to the temperature and pressure conditions by Kim et al. (2011). Hundreds of wire wraps are utilized to generate an electric field to induce high-speed rotation in the compressors of such systems. These wires produce high temperatures, creating the potential for lubricant vaporization and thus a combustible gas mixture. Kim et al. devised a vessel to contain large amounts of lubricating oil to simulate auto-ignition under conditions encountered in these compressors. Mainly qualitative results were produced. Auto-ignition was shown to have a strong dependence on the vaporization rate of the lubricating oil, test pressure, and oxygen content. Observations were taken at pressures up to 30 atm and over temperatures between 420 and 490°F (216 and 254°C). These results indicate auto-ignition of the lubricating oils at temperatures much below their stated auto-ignition temperatures, and they report ignition temperatures much closer to the flash point (~340°F or 170°C). This result implicates the conditions seen within an air conditioner are potentially hazardous particularly in the presence of oxygen. The investigation did not, however, provide a characterization of the gas mixture composition (to resolve oil/air ratio), and important parameters such as ignition delay time (τ_{ign}) were not addressed.

Sun et al. (2019) discussed the fire potential oils pose to wind turbines. Thermogravimetry-differential scanning calorimetry (TG-DSC) was used to investigate the thermal decomposition of three oils found in wind turbine gear oil, transformer oil, and hydraulic oil. Additionally, thermodynamic parameters were calculated using Starink and Ozawa-Flynn-Wall (OFW) methods where calculated values were then compared to measured ones. Fourier transform infrared (FTIR) spectroscopy at 200°C was additionally used to probe the thermal decomposition of the oils. Mass loss rates for each oil are reported (-5.24%/min, -7.15%/min and -4.88%/min, for gear oil, transformer oil, and hydraulic oil, respectively). The transformer oil was noted to have the highest fire hazard potential. While TG-DSC and FTIR were used and some data were reported, the study's use of these methods was largely for proof-of-concept purposes, and the need for further investigation was highlighted.

Interestingly, lubricant auto-ignition within air guns has been shown to cause energy gains of up to 50% (Cardew and Cardew, 1995). It was shown that the rapid compression of the air behind the projectile results in enough of a pressure and temperature increase to cause lubricant ignition, which actually aids in the process of giving the projectile momentum.

Lubricant Ignition in Internal Combustion Engines

As discussed, lubricating oil is also a known source of LSPI leading to knock in ICEs. This phenomenon continues to be an issue for manufacturers as engines are continually downsized, requiring pressures within the combustion chamber to increase (i.e. turbocharging) to achieve the same power (Kassai et al., 2016). Lubricating oil coating the walls of the combustion chamber brings the lubricating oil into direct contact with the combusting gases. Due to this major interaction, several studies have investigated the influence of lubricants on combustion properties for a given fuel. Particularly, the interaction of lubricating oil in a gasoline engine has been studied to examine the effect on an engine's knock propensity (Kassai et al. 2015). These studies show the lubricant promotes ignition, due mainly to the long carbon chains of the lubricant (Siregar and Nugroho 2014). It should be noted that lubricant composition has been indicated as an important parameter in its ignition propensity (Cooper et al. 2021). Further details on the mechanisms for which lubricating oil ignition

in the combustion chamber causes low-speed, pre-ignition (LSPI) in IC engines have been discussed in the literature (Kassai et al. 2015, and Kassai et al. 2016). Kassai et al. (2015) in particular further describe the lubricant droplet hotspot creation discussed earlier.

Overall, little information can be found in the literature regarding lubricant oil ignition in gas turbines, and chemical kinetics data are nearly non-existent. In preventing lube oil auto-ignition, a fundamental understanding of the chemical kinetics of lube oil ignition is desirable. Particularly in choosing a lubricating oil for a gas turbine system, auto-ignition properties are important considerations. Even qualitative comparisons between different lubricants would allow turbine designers and users some additional information when choosing a suitable lubricating oil. However, additional information on the lubricant's composition may be required.

Lubricant Oil Composition

As mentioned earlier, the recipe used by lubricant manufacturers is normally highly proprietary. Step one in understanding a compound's combustion is detailing its molecular composition, making lubricants particularly hard to describe. To circumvent this obstacle, gas chromatography was utilized to produce estimations of molecular distribution and average carbon number; the method mainly focused on alkanes and aromatics (Cooper et al. 2021). However, the lubricants include numerous other compounds that could not be resolved by the method used. Further investigation is needed to fully characterize the lubricants and their components. Initial work was done by the authors, presenting a limited two-dimensional gas chromatography (GCxGC) of a gas turbine lube oil suggesting most of the lubricant consists of alkanes with carbon numbers between 27 and 32 (Cooper et al., 2021). More detailed GCxGC analyses on automotive lubricants suggest a range of C17-34 (Kuti et al., 2015; Wang and Zhang, 2007). Additionally, n-hexadecane (C₁₆H₃₄) has been recommended as a suitable surrogate for lubricant-fuel mixtures in internal combustion engines (Mitsudharmadi et al., 2019; Distaso et al., 2020). Several chemical kinetics models for n-hexadecane have been developed, namely those from Lawrence Livermore National Laboratory (LLNL) and the CRECK modeling group (Westbrook et al. 2009 and Ranzi et al. 2014). While n-hexadecane is not nearly the average C₃₀ molecule suggested previously, it could provide an initial step in modelling efforts, especially since few models include molecules larger than n-hexadecane.

Shock-Tube Studies

Shock tubes have been shown to be useful tools in investigating chemical kinetics of fuels in regimes relevant to gas turbine combustion, particularly in understanding pollutant emission pathways (Cooper et al. 2020). They have also contributed greatly to our fundamental understanding of gaseous fuel combustion for gas turbines, including combustion relevant to the Allam-Fetvedt Cycle (Hargis and Petersen, 2015; Pryor et al., 2017; Allam et al., 2017); fundamental natural gas, hydrogen, and NO_x kinetics (Cooper et al., 2020; Mulvihill, 2019); and kinetics of liquid aviation and ground transport fuels (Alturaifi et al., 2019; Cooper et al., 2020; Cooper et al., 2021). However, shock-tube studies have largely been limited to kerosene-based fuels and become increasingly difficult to apply to larger and larger molecules (Cooper et al., 2021; Cooper and Petersen, 2021; Hargis et al., 2020, 2021). That is, shock tubes had not been applied to lubricants prior to the recent work at TAMU, and additional strategies were required for this application.

Hot-Surface Ignition Studies

Flammable liquids igniting on hot surfaces in the absence of a flame or spark is a safety concern in engines and other mechanical devices where high temperatures are present. This occurrence is commonly known as hot-surface ignition (HSI) and is probabilistic by nature. HSI is influenced by the flammable liquid's thermophysical and chemical properties (specific heat, heat of vaporization, ignition activation energy, etc.) and also is influenced by local environmental parameters like air currents, surface material, length scales, surface roughness, surface cleanliness, surface temperature, liquid drop height/velocity, and liquid volume. While it is commonly accepted that the dominant factor driving HSI is the temperature of the surface, maintaining careful control of all the other factors affecting ignition probability is crucial when developing a reliable, lab-scale experimental evaluation technique. There are currently no available standards for HSI characterization of flammable liquids, so engineers and scientists have developed their own hardware and techniques.

In 1980, Myronuk presented an extensive study of HSI of hydraulic fluids and aviation fuels on various metal surfaces, including austenitic stainless-steel (SS, type 321), titanium, Inconel (X750), and molybdenum (Myronuk, 1980). In their study, they noted the effect of local air velocity and the oxidation level of the metal surface on the ignition results. The sensitivity of the surface properties such as roughness and heat flux were explored by Bennet (2001). Demetri and White (1985) used a liquid spray rather than single droplets and also developed a method to determine the ignition delay time using optical emission from the burning fuel. Single droplets were utilized by Colwell and Reza (2005) in an experimental setup that was designed to reduce the effect of local air currents on the HSI results. Several studies from Exponent, Inc. have appeared in the literature for a range of automotive fluids (Davis et al., 2006, 2009; Somandepalli et al., 2008). Byers et al. (2007) presented a very comprehensive study using a gasoline (standard 87 Octane) to characterize the effect of liquid volume, surface material, and surface temperature variation on their HSI results. Two other studies involving the ignition of single droplets from a set height were performed by Ebersole et al. (2009) and Goyal et al. (2017). Few HSI data exist in the open literature for lubrication oils.

EXPERIMENTAL DETAILS

Shock-Tube Technique

The high-pressure shock tube (HPST) facility at TAMU was used to generate high-temperature conditions. The facility consists of a 15.24-cm inner diameter, 5.03-m-long driven section. The driven section is separated from an extended, 5.11-m-long driver section by a 0.25-mm thick polycarbonate diaphragm. A cross-shaped cutter downstream of the diaphragm allows for repeatable and clean diaphragm opening. Pressure transducers along the last 1.44 m of the driven section allow for calculation and extrapolation of the incident shock wave velocity to the endwall location. Using this velocity along with the initial pressure and temperature in the driven section allows for calculation of the post-reflected shock temperature and pressure to within 0.8% and 1.0%, respectively. Upon shock reflection, a spray injection technique, utilizing an automotive injector to send air through a 0.2-mL droplet of oil, introduces a fine mist of oil into the high-temperature air. Note that the droplet size matters from test to test since it represents a set amount of fuel by mass; changing the mass will alter the fuel-to-air stoichiometry and hence the reactivity of the fuel-air mixture once the droplet is converted to gas.

Figure 1 shows a schematic of the injector mounted at the endwall, relative to the passage of the shock wave and the resulting high-temperature conditions in the region between the endwall and the reflected shock. To observe ignition, an OH* chemiluminescence diagnostic utilizes a window at the sidewall location (1.6 cm upstream from the endwall) of the shock tube to focus light emitted from combustion into a photomultiplier tube filtering light to 306 nm. The resulting pressure and OH* profiles allow for collection of the ignition delay time. Figure 2 presents a photograph of the shock-tube facility, showing the endwall region with the lubricant injection hardware attached. Previous work describes the facility and oil injection technique in further detail as well as an estimation of ignition delay time uncertainty of $\pm 30\%$ (Cooper et al., 2021).

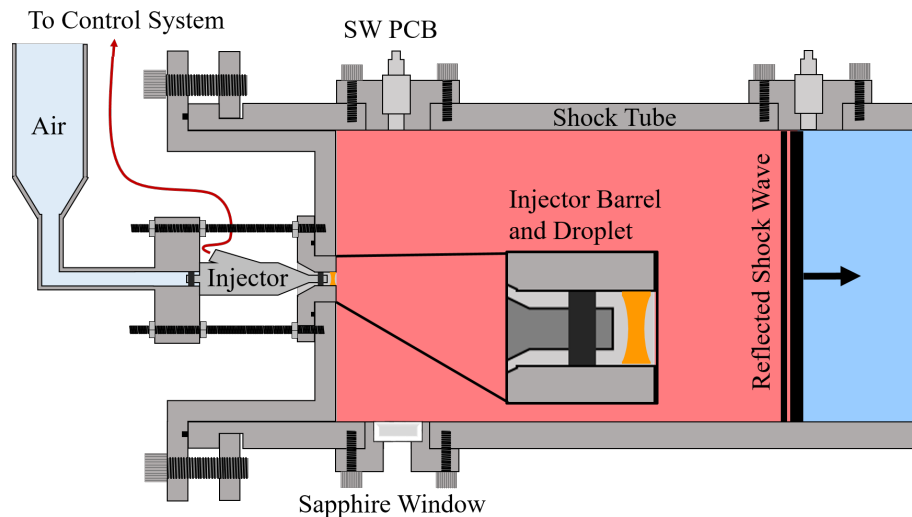


Figure 1: Schematic of the lubricant spray injection setup. A magnified view of the injector barrel is shown. The sapphire windows allow for optical access for OH* emission and laser scattering, and the piezoelectric transducer for pressure measurement is shown in the upper port.

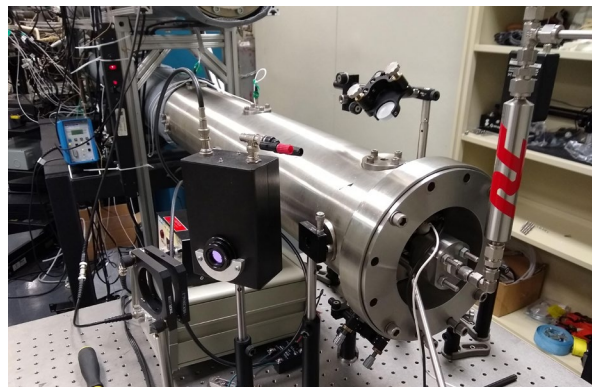


Figure 2: Shock-tube facility located at the Turbomachinery Laboratory facility at TAMU, showing the last portion of the driven section and the injection hardware mounted to the endwall.

Chemical kinetic modeling was performed using the Chemkin 19.0 package from Ansys (2018). A closed homogeneous reactor, under a constant volume assumption, was used to represent the ignition delay time experiment. As discussed, the literature suggests using n-hexadecane as a surrogate for lubricant ignition kinetics. Therefore, literature kinetics mechanisms from LLNL and the CRECK modeling groups for n-hexadecane were used to compare to experimental results (Westbrook et al. 2009 and Ranzi et al. 2014).

HSI Technique

A schematic of the experimental setup at TAMU is shown in Fig. 3, which details the main components: the hot plate, the heating system, and droplet production. Three cartridge heaters with internally embedded thermocouples were sealed inside of a 304 SS plate with high thermal conductivity paste (silver-filled conductive paste, 597-C). The cartridge heaters are individually controlled by 3 PID controllers and can reach temperatures as high as 750°C (1382°F). The SS block is surrounded on 4 of its 6 faces by insulation to protect the fume hood it is contained within and to minimize heat losses. The apparatus is located within a fume hood so that the vapors from evaporating, unburned fuel droplets as well as from combustion products from burned droplet can be safely exhausted. A scientific pipette is utilized to dispense liquid droplets with volumes up to 20.7 μL. The pipette is held in a burette stand that allows for variation of the droplet height. The height was set such that the liquid droplet did not break up on impact with the surface (~10 cm currently). A calibration curve was produced that correlated the surface temperature (measured using a thermocouple probe at the test location) to the internal temperature of the cartridge heaters.

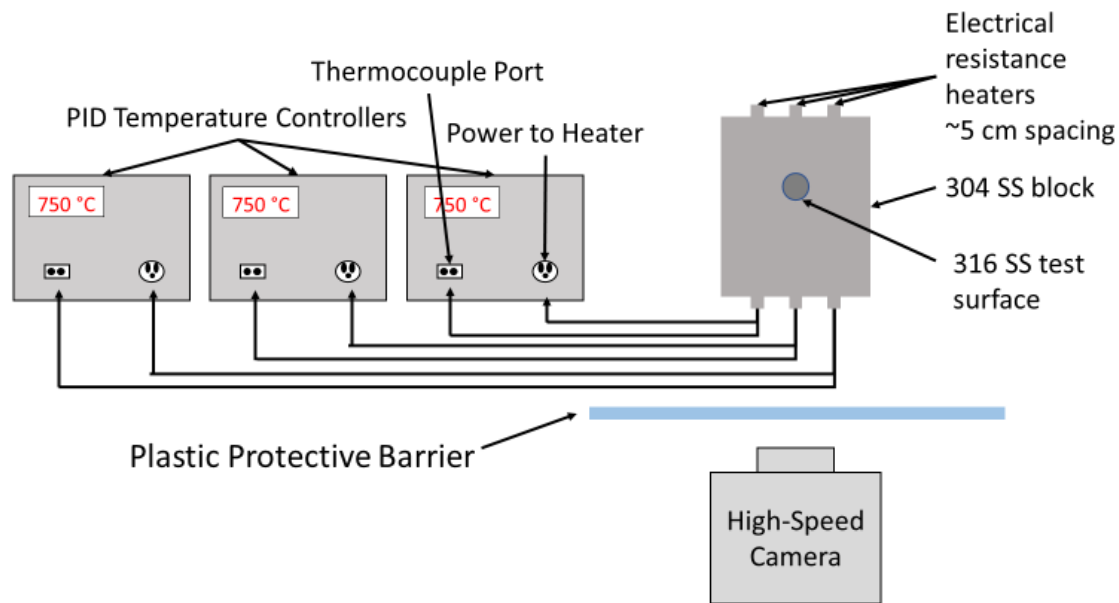


Figure 3: Schematic diagram of the HSI experiment at TAMU.

Prior to testing, the SS block's core temperature is set to the desired value and given enough time for the surface to reach the desired, steady-state temperature. A 20.5-μL droplet of the selected fuel is released from the pipette and falls to the hot surface where it evaporates and may or may not ignite. A total of 20 data points are typically recorded at each temperature of interest for each fuel, since the ignition event is stochastic by nature. The ignition probability of each fuel at a given surface temperature is then computed as the total number of ignition events divided by the total number of trials.

The impact of variations in the surface temperature of the plate; level of oxide coating; surface cleanliness (due to residue from previous tests); and motion of the droplet along the plate were minimized by designing a reusable test surface. A photograph showing the removeable disk is seen in Fig. 4. The removable test surface is placed into a recess in the block's surface (as can be seen in Fig. 4) to ensure consistent placement and to improve heat conduction. The top of the test surface was given a slight bowl shape to constrain droplet motion, thus reducing the effects of temperature gradients on the surface and improving video capture capabilities. Replacement of the disk with a fresh one simplifies the cleaning process and minimizes any oxide-layer growth problems. An additional layer of insulation was added to the top surface to add control of the exposed surface area and improve the temperature capabilities of the experiment by reducing radiative heat losses (Fig. 4). A K-type thermocouple is embedded just beneath the center of the test surface to actively monitor the sub-surface temperature during tests. Side-placed air barriers (plexiglass sheets) prevent air currents from blowing across the surface, thus maintaining a quiescent environment. Further details on the design and characterization of the apparatus can be found in the thesis of Teitge (2021).

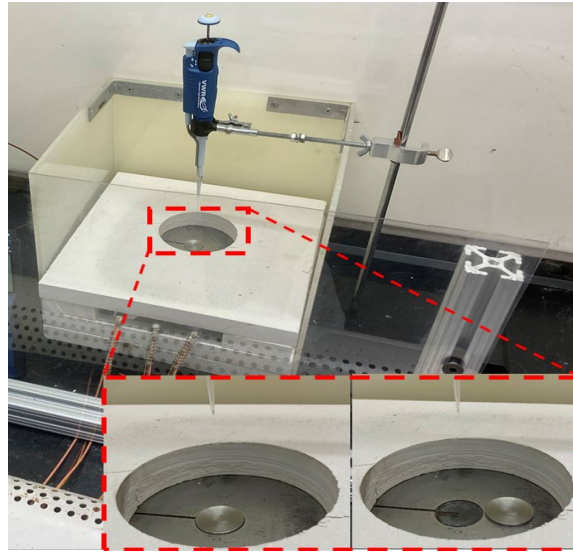


Figure 4: Photograph of the pipette and test region of the hot plate. Note the insulation (white) atop the plate except for where the isolated, removable test piece is located. The magnified view shows a sample test piece mounted in place (left) and set aside (right).

RESULTS

Shock-Tube Tests

Utilizing the shock tube and spray injection technique described above, ignition delay time data were collected for an off-the-shelf turbine oil (ISO VG 32). The results of the ignition delay time experiments for the ISO VG 32 oil are shown in Fig. 5. Each data point denotes a single experiment. Note that the error bars shown on the two sample points are meant to be representative of the range of errors (in both T_5 and τ_{ign}) for all the data.

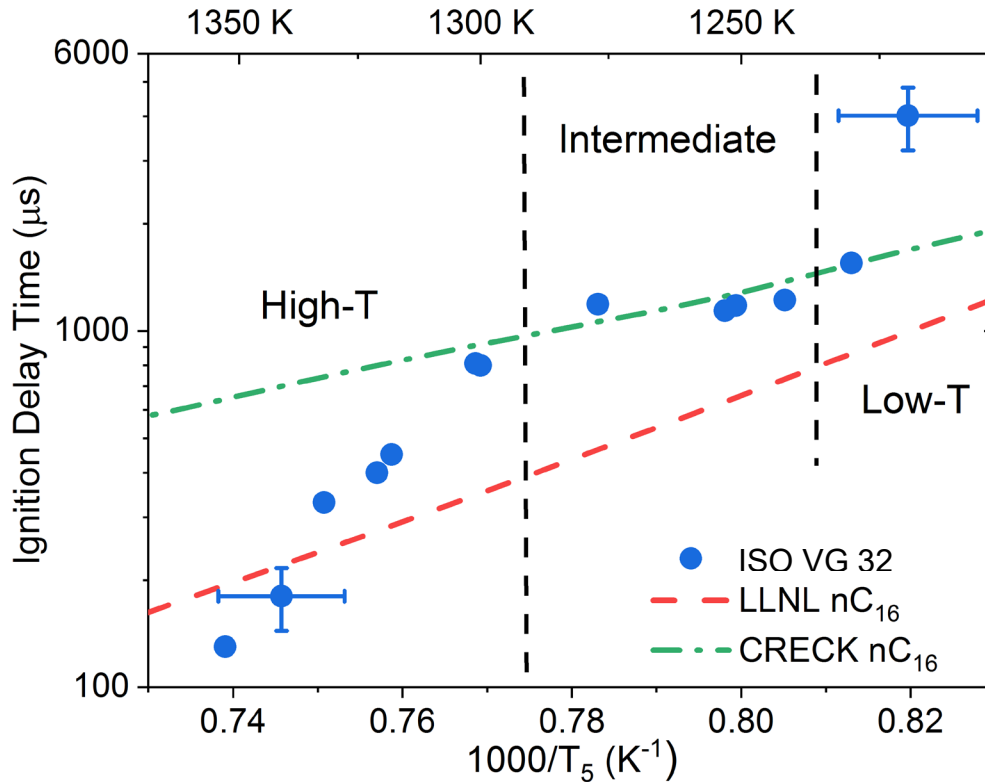


Figure 5: Ignition delay time plot for the ISO VG 32 oil. T_5 is the temperature behind the reflected shock wave, or in other words the test temperature.

Three main features are seen in the resulting ignition delay time curve shown in Fig. 5. That is, a high-temperature, Arrhenius-like region, an intermediate region where little dependence of ignition delay time on temperature is observed, and finally a return to Arrhenius-like behavior in the lower temperatures. In subsequent experiments with other oils (not presented here), it has been shown that some oils display multi-zone behavior like that seen in Fig. 5 (i.e., the changes in slope on the $1/T$ plot), while others present a single, linear trend on the Arrhenius plot. This method of determining this chemistry-driven ignition delay time for the oils has proven to be valuable not only for ranking and comparing various oils in terms of their ignition behavior, but the resulting data can be used in a more fundamental manner to better understand the chemical kinetics of the ignition process. Such data lead to chemical kinetics model development and refinement. Such a model is composed of the individual, elementary chemical reactions steps that represent the intermediate collisions between the molecules in the reacting mixture (from original fuel and oxidizer molecules, to intermediate molecules and radical species, to the final products containing mostly CO_2 and H_2O).

It is interesting even at this early stage of the lube oil ignition studies to compare the test results with the predictions of existing chemical kinetics models. However, there are unfortunately no existing models for gas turbine (or any, really) lube oil fuels, so work is needed in this area. Nonetheless, the authors can compare the results with a model made for very large hydrocarbons. Also shown in Fig. 5 are model predictions made by the n-hexadecane kinetics mechanisms from LLNL (Lawrence Livermore National Laboratory) and CRECK. As discussed above, the lubricant consists of not only very large molecules, but also numerous non-alkane-based additives that can significantly affect the ignition kinetics. So, while n-hexadecane may not be a suitable surrogate for the ISO 32 oil ignition, the addition of chemical kinetics chemistry for its many additives may aid significantly in the ignition delay time prediction. As seen in Fig. 5, the two models given results in the vicinity of the new data for the ISO 32 oil, but they do not capture the changes in slope between the different temperature regimes. The CRECK model seems to capture well the slope and magnitude of the ignition delay times at the intermediate-to-low temperatures, although this could be fortuitous since the model was not designed for lubrication oils. More work is needed to better understand and model the ignition chemistry of lube oils.

HSI Tests

For all experiments completed using the current experimental setup, one droplet was dispensed on a test surface at a time. Ten total drops were tested on a single test surface before it was replaced with a new test surface. In general, an additional ten drops were tested at the same temperature, such that 20 total drops were tested at each temperature. It was observed in prior experiments that 20 droplets per temperature were sufficient to determine the ignition probability of the fuel at one temperature. After the ignition probability was determined at one temperature, the temperature was incremented, and the process was repeated. This iterative process continued until HSI values ranging from 0% to 100% were gathered for the fuel (or oil) being studied. This procedure yields a measurement resolution of ignition probability of 5% at each temperature; however, the stochastic nature of these phenomena yield scatter that is on the order of $\pm 10\%$. Implementing more drops per temperature could improve the ignition probability resolution, but with minimal gains considering the time it takes to collect the extra data (a manual process) and the ultimate repeatability of the data.

The ignition probability can be described with a logistic regression curve fit of the form:

$$P(I) = \frac{100}{1 + \exp(-k*(T - T_{50}))} \quad (1)$$

where k and T_{50} are empirical constants that describe the ignition behavior of the fluid. Equation 1 is a logistical curve that is commonly used in a range of scientific fields to model the behavior seen in HSI data. That is, the probability should be 100% at higher T and zero percent at lower T while maintaining a near-linear trend for T in between these two limits. The T_{50} coefficient corresponds to the temperature where 50% ignition probability is expected, and the k coefficient describes the rate of change of ignition probability with temperature. The LTI (lowest temperature for ignition) and HTI (highest temperature for ignition) are important markers for the behavior of the liquid. The LTI represents the temperature where ignition is first recorded for the fluid. This lower bound is important information from a safety standpoint since it represents a threshold for the temperature of machinery surrounding the fluid. A safety factor equal to at least the temperature difference between surface temperature increments should be utilized for this value. The HTI represents the highest temperature without ignition. This limiting temperature is an important value for engineers designing propulsion or power generation systems that want to utilize HSI to their advantage. The ignition delay time for the fuel can also be critical for these systems, since the working fluids are generally not resting in a quiescent environment, such as the one emulated in the experiments conducted herein.

Representative HSI data and logistic regression curve fits are shown in Fig. 5 for two ISO 32 lubricating oils. The empirical coefficient and LTI/HTI data for these oils are as follows. The k values (from Eqn. 1) are 0.038 and 0.053 $1/^\circ\text{C}$ for the two ISO 32 oils; T_{50} of 573°C for both; LTI of 510 and 520°C , respectively; and HTI of 616 and 627°C , respectively. Similar general HSI behavior and logistic empirical coefficients are observed for both lubricating oils. The minor difference in k coefficient falls within the statistical uncertainty of these coefficients (90% confidence interval).

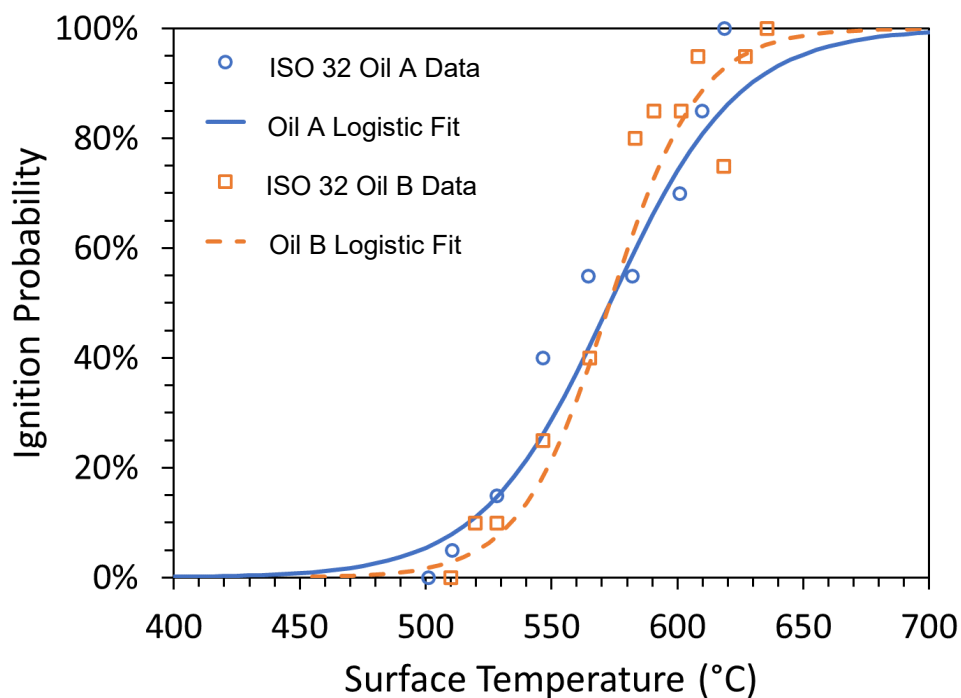


Figure 6: Lubricating oil ignition probability data for two ISO 32 oils. Data for two lubricating oils with corresponding logistic regression curve fits in the form of Eqn. 1 are shown.

As expected, ignition probability generally increases with temperature. For the present results, it appears that both lube oils presented in Fig. 6 behave similarly with respect to HSI, but whether or not this is a basic result for all lube oils cannot be determined at this time. More data are required over a range of oil types and sources before any further conclusions or trends can be discerned. Also, in general, there is a lack of high-quality HSI data provided within the literature. For instance, there are no data provided within the literature for these lubricating oils, which make the datasets such as the one in Fig. 6 the first of their kind. This strong lack of comparable data within the literature makes it difficult to compare the current experiment to others with similar datasets. The authors are currently conducting additional experiments to produce HSI data for a range of lube oils of interest to the turbomachinery community.

FUTURE WORK

For future shock-tube ignition experiments, off-the-shelf lubricants will be studied to understand their ignition characteristics. This selection will allow for a simple, qualitative comparison between currently available lubricants. However, to understand the characteristics further, a base mineral oil and polyester (synthetic lubricant base) will be used as a baseline for comparison with additives (i.e. anti-oxidants, detergents, corrosion inhibitors, demulsifiers, and anti-foaming agents) to observe the relative effects each additive has on the base oil. To accomplish this, several concentration amounts will need to be examined for each additive (1, 5, and 10 vol. %). In this way, the relative effect each additive has on the base mineral oil can be extrapolated. It should also be noted that an experimental method that can extend the test temperatures to lower values (while still observing ignition events within the test time) should be considered, to extend the results to lower T. A method such as a rapid compression machine would be appropriate for such tests.

As lubricants and additives are very complicated mixtures of long-chain hydrocarbons, a smaller test fuel (n-hexadecane and Jet-A) can be used to study the ignition process on a more fundamental level. In this way, ignition delay time data for n-hexadecane and Jet-A can be collected using both the spray injection technique and the standard shock-tube heating method. This procedure will be important in isolating certain effects cause either by the injection technique or by the large hydrocarbon itself. Additionally, chemical kinetic models are available for these molecules, allowing for a more detailed examination of the chemistry. These data will initially allow for a qualitative comparison of relative reactivity for each mixture, which will be valuable in understanding the global effect of different additives. However, chemical kinetic modeling is required to further understand the fundamental details of the lubricants' ignition behavior.

The HSI experiment presented herein is the product of several design iterations which has yielded one of the most well-controlled experiments for HSI in the current literature. Future work for the project includes studies on the ratio of exposed surface area to droplet volume to determine optimal values for these in this configuration of the experiment. With these values, a perfected experiment can be assembled with new heaters to allow testing at higher temperatures. This modification for higher temperatures would allow for testing

of fluids with higher LTIs, such as common jet fuels, along with any new fuels being currently developed. Hence, the new rig originally designed for lubrication oils can be used for characterizing a wide range of liquid fuels and propellants.

CONCLUSIONS

Fundamental information on the ignition behavior of lubrication oils used in common turbomachinery is needed for better understanding of the physics and chemistry of the combustion process and for future prevention of unwanted ignition. The results of a literature search indicate that there are few if any such data available in the open literature. To help provide the missing data and related insight, new capabilities were established at TAMU. A spray injection technique was used to observe lubricating oil ignition within a shock tube. Particularly, an off-the-shelf lubricant, ISO VG 32, was ignited behind reflected shock waves. Ignition delay time data were collected for this lubricant, and several features were observed in the resulting curve. That is, an Arrhenius-like high-temperature region, a region of little temperature dependence on ignition, and a low-temperature region that appears to return to Arrhenius behavior. Chemical kinetic modeling was performed using two kinetics mechanisms from the literature for n-Hexadecane (as suggested by the literature for a surrogate for lubricant ignition chemistry). However, these models were unable to reproduce the results. Further work is needed to isolate the effects additives have on ignition of a base mineral oil (petroleum base lubricant) or polyol ester (synthetic lubricant). A second experiment designed to characterize the hot-surface ignition behavior of lube oils was also established at TAMU. Data for two off-the-shelf lube oils were presented, both with similar results for the T_{50} values.

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